Taking the soil-structure interaction into account in assessing the loading of a structure in a mining area

Olivier Deck, Marwan Al Heib, Françoise Homand

Revue "Engineering Structures"

Taking the soil-structure interaction into account in assessing the loading of a structure in a mining subsidence area.

DECK* Olivier, AL HEIB* Marwan, HOMAND** Françoise

* : Laboratoire Environnement, Géomécanique et Ouvrages (LAEGO-INPL-INERIS), Ecole des Mines de Nancy, parc de Saurupt, 54042 Nancy cedex. (Tel : (33) 03.83.58.42.89, Fax : (33) 03.83.53.38.49, deck@mines.u-nancy.fr; heib@mines.u-nancy.fr

** : LAEGO-INPL-INERIS, Ecole Nationale Suoèrieure de Géologie, rue du Doyen Roubault, 54500 Vandoeuvre-lès-Nancy. Francoise.Homand@ensg.inpl-nancy.fr

Abstract

Underground mining of raw materials is often the cause of ground movements at the surface. Whether planned or accidental, such movements can cause considerable damage to structures located within the area of influence of underground mining works. Examples are the recent subsidences that took place at the end of the 1990s in the Lorraine iron mining field. A better understanding of how ground surface movements can be imparted to the supported structure and damage it is necessary. Indeed, it is too often considered that damage depends only on ground strain and no account has been taken of soil-structure interaction phenomena, which may affect considerably the structural behaviour.

The stiffness of a structure is quantified in comparison to that of the ground as regards the various movements of the ground surface. This investigation highlights situations in which ground movements are integrally imparted to a structure. When this is not the case, the resulting complex soil-structure interaction phenomena is analysed. For this purpose, a finite-element software is used to generate models incorporating the ground material and a supported rigid structure. The ground movements are broken down into two basic movements in order to highlight the impact and the relative importance of one of theses movements : ground curvature and horizontal strain. Structural stresses are quantified for different mechanical properties of the ground and the structure, as well as for different amplitudes of ground movement. This investigation made it possible to devise a methodology for analyzing structures in mining subsidence areas in order to determine cases in which soil-structure interaction phenomena must be considered. The investigation made it possible to hierarchically organize the ground and structure parameters, the variability of which has a significant effect on the behaviour of the structure affected by mining subsidence.

Key words: mining subsidence, soil-structure interaction, numerical methods, equivalent stiffness.

1 Introduction

The industrial need for large quantities of raw materials at an acceptable cost has led to large underground mines and quarries. Because of the extraction methods, such underground mining works create underground voids which may cause mining subsidence phenomena, i.e. significant movements at ground surface. This sometimes results in serious damage to structures built in the area of influence of such movements. Mining subsidence is planned in the case of mining methods that incorporate the caving-in of the created cavities as work proceeds ("caving-in" method in coal mines, for example). On the other hand, mining subsidence is of a highly accidental nature when it takes place over mines and quarries that use methods based on abandoned rooms and pillars. Indeed, in the latter case, the operator has deliberately left in place natural or artificial pillars sized to withstand the weight of the overburden. Recent cases of mining subsidence that have taken place in the Lorraine iron mining area (France) denote the hazard of such mining works when left abandoned.

The cases of subsidence in Lorraine led public authorities to carry investigations over the entire Lorraine iron mining field. These investigations highlighted the existence of about 2000 hectares of urbanised areas undermined by abandoned works consisting of rooms and pillars. A hierarchy of the hazard was derived : from the risk of caving-in to the risk of structures being damaged by planned subsidence. The second part is the topic of this paper. Which methodology can be proposed to predict the damage likely to affect a structure located in a hazard area, in which considerable strata movements may occur? A more fundamental question may be formulated: are ground level movements imparted integrally to the structure or does this involve soil-structure interaction phenomena caused by significant differences in stiffness between the ground and the structures? As long as the ground movements are imparted to the structure integrally, a geotechnical engineer can inform a civil engineer of the predicted importance of such movements. The latter can then apply these movements to the foundations of a structure in order to assess their impact. If, on the other hand, there is strong interaction between the ground and the structure, neither the geotechnical engineer nor the civil engineer can assess the structure loading.

The ground movements describe caused by a mining cave-in were first described. Then a method is presented to characterise the relative stiffness of a structure and of the ground, in terms of the surface movements generated during a subsidence. Finally the unfavourable case of a strong interaction between the ground and the structure is assumed to investigate the relative effect of different types of ground movement on the structure behaviour.

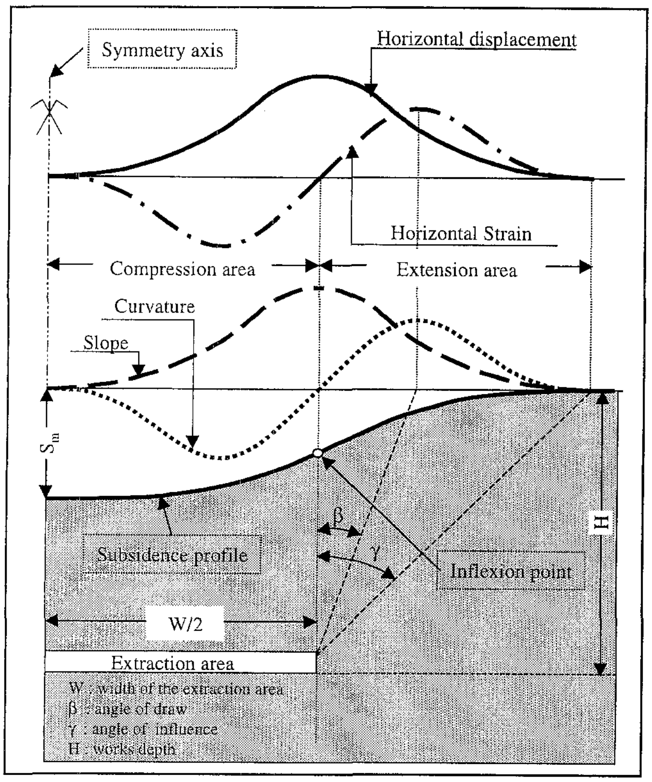


Figure 1 : Description of ground surface movement as a result of a mining subsidence.

2 Description of the phenomenon

Mining subsidence often produces significant horizontal and vertical movements at the ground surface (Figure 1). The maximum value "Sm" of the vertical subsidence is usually considered as a characteristic of the trough. However, the horizontal strain of the ground, its curvature and its slope, are the three movements loading structure and causing structural damage. The maximum values observed for these parameters can be disastrous for a structure if the movements are imparted integrally (Wagner and Schümann [1]). The measurement of these parameters entails significant difficulties either when a site of mining subsidence is instrumented, or in a case where cave-in has not yet taken place and prediction is regarded. The real measurements of movement often reveal that the vertical movement is in agreement with its theoretical value, but the slope and the horizontal strain deviate slightly from theory and the curvature even more so, as shown in Figure 2 to be compared with Figure 1. The increasing difference between theory and practice can be readily appreciated since the slope, strain and curvature are in reality the primary or secondary derivatives of the displacement. The differences between the theoretical and real displacement are then considerably amplified. When movement predictions are involved, this difficulty entails the presence of a large number of empirical methods for predicting vertical displacements, a smaller number of such methods for predicting strains and virtually no method developed for the curvature or slope (Whittaker et Reddish [2]).

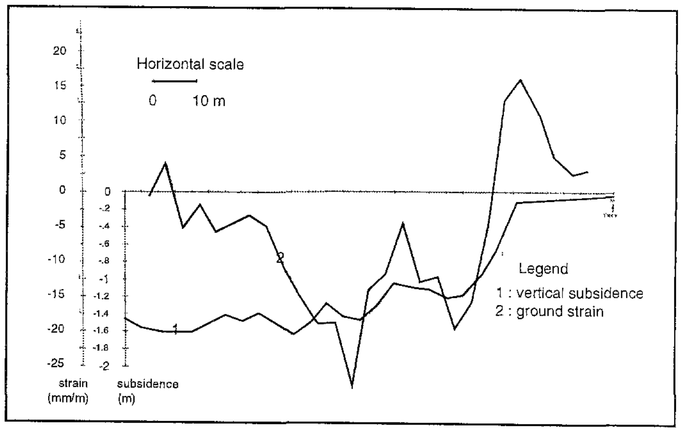


Figure 2: Example of a mining cave-in in South Africa: vertical displacement and horizontal strain, Merwe [3].

regard to horizontal strains, Speck and Bruhn[7] merely consider the development of shear stress at the soil-structure interface or the increase in the horizontal stresses on buried parts of the structure. Kratzsch[5] recalls a former experimental investigation carried out on a physical model, reproducing the failure occurring in the ground because differences in horizontal strain.

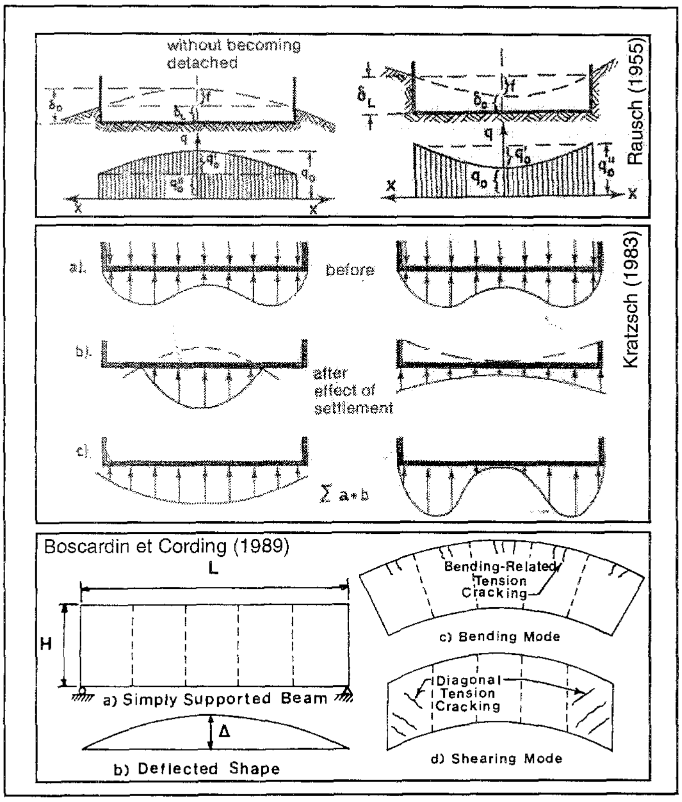


Figure 3: Behaviour of a structure in a curvature area

Methods for predicting structural damage generally use firstly the definition of the threshold value of the strain and curvature from which a damage is expected, and secondly behaviour diagrams providing an overall view of the behaviour of the structure under the effect of each load component. A few examples of behaviour in a curvature area and in a strain area are shown in the diagrams of Figures 3 and 4 respectively. In a curvature area, the structure is sometimes considered to be rigid, making possible to estimate the distribution of vertical stress in the ground (Rausch [4] and Kratzsch [5]). On the other hand, Boscardin and Cording [6] consider the structure to be flexible and to behave like an isostatic beam whose curvature is imposed by that of the ground and for which the horizontal strain of the lower fibre of the beam is imposed by the horizontal strain of the ground. With

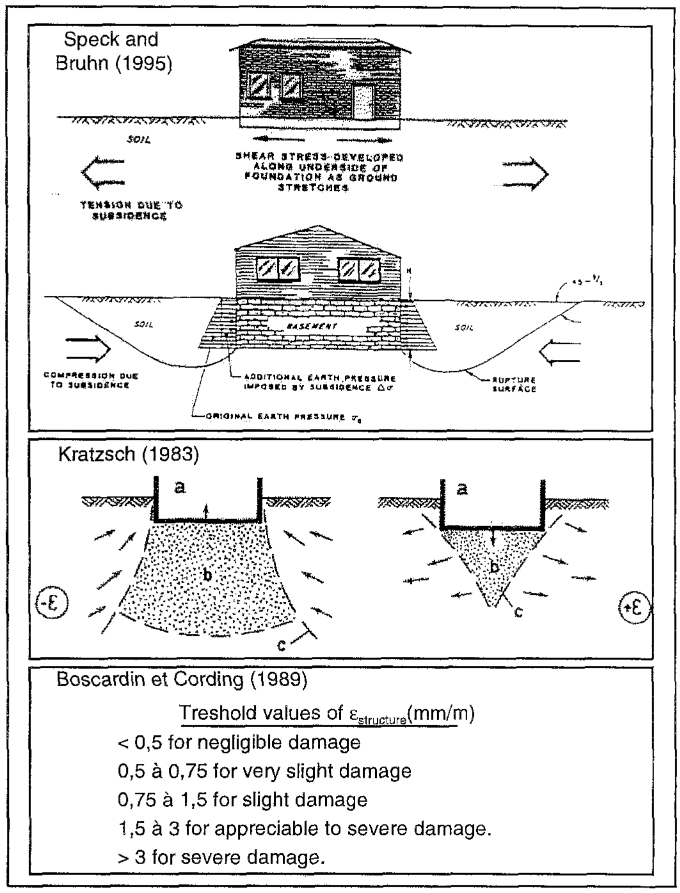


Figure 4 : Behaviour of a structure in a horizontal strain area

The outcome of these few examples is that the fundamental question is whether ground movements are imparted integrally, partially or not at all to the structure. "Integrally" means that the structure is loaded by displacements, "not at all" means that the structure is loaded by stresses, whereas "partially" indicates the existence of complex soil-structure interaction phenomena.

3 Characterisation of the relative stiffness of a structure compared to the ground

The investigation of soil-structure interaction require a clear definition of stiffness. Two stiffness parameters are involved : a first stiffness parameter characterises the behaviour of the structure as compared with that of the ground as regards surface curvature ; a second parameter characterises the compared behaviour as regards the ground horizontal strain. We propose to characterise the ground stiffness and the structure stiffness as regards these two parameters of ground movement in order to determine the situations in which one or the other of these parameters is integrally transmitted to the structure.

3.1 Estimation of the stiffnesses as regards ground curvature

The reasoning is based on calculating the mechanical energy required either to impose the ground curvature on a structure, or to impose a structure horizontally on an initially curved ground. The scenario calling for the lowest energy is considered the more likely. Figure 5 provides schematic illustrations of the possible scenarios for a concave area.

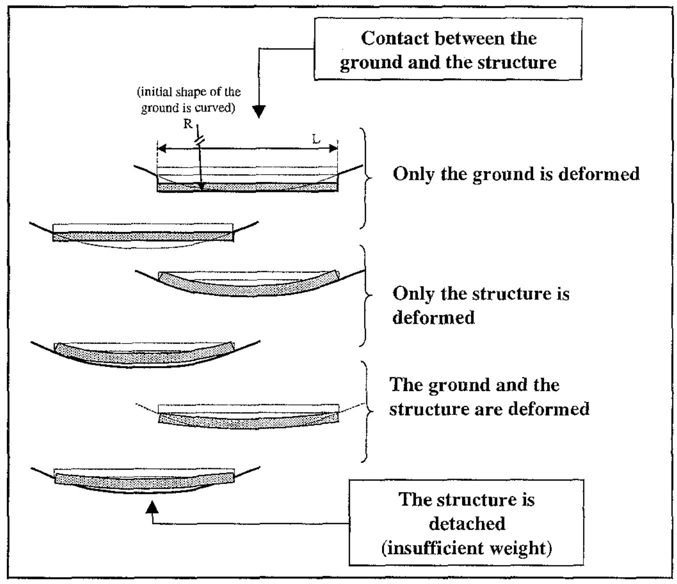


Figure 5 : Various possible behaviours of a structure in a concave curvature area

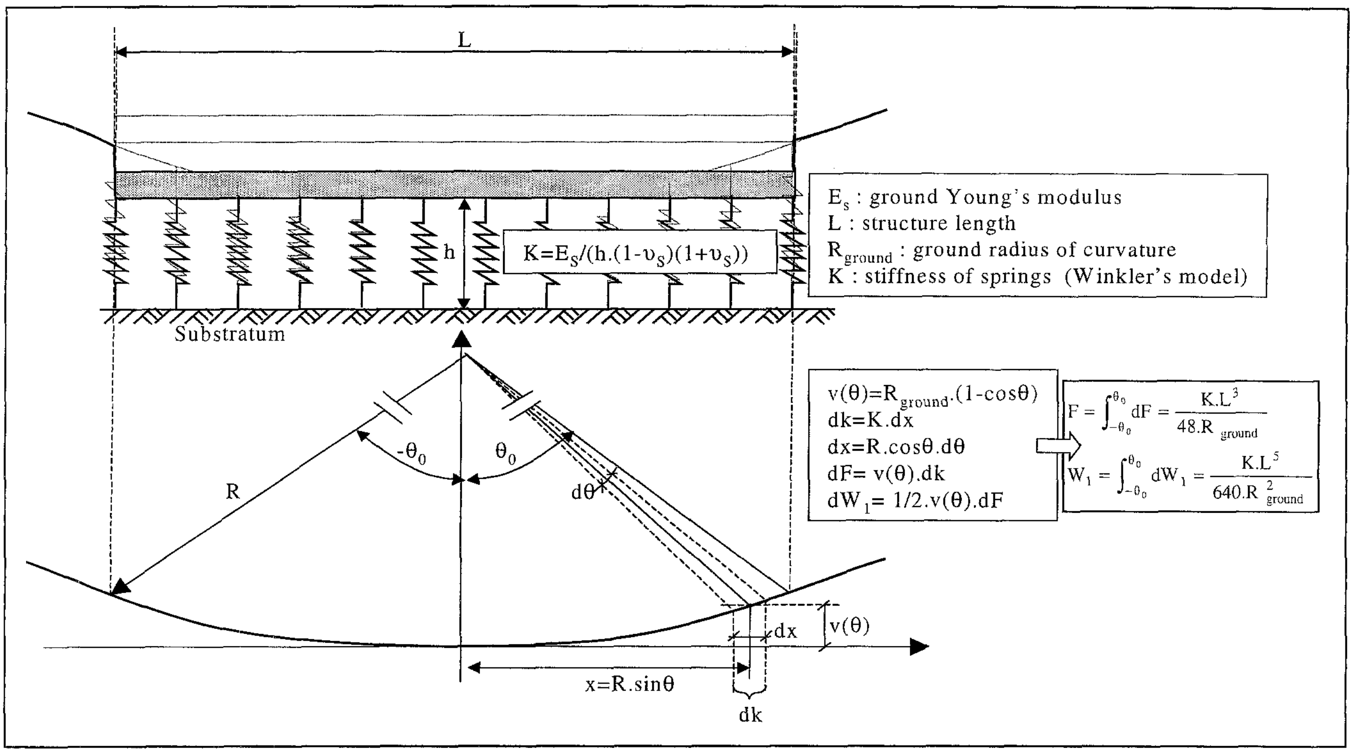


Figure 6 : Calculation of force and work required to deform the ground.

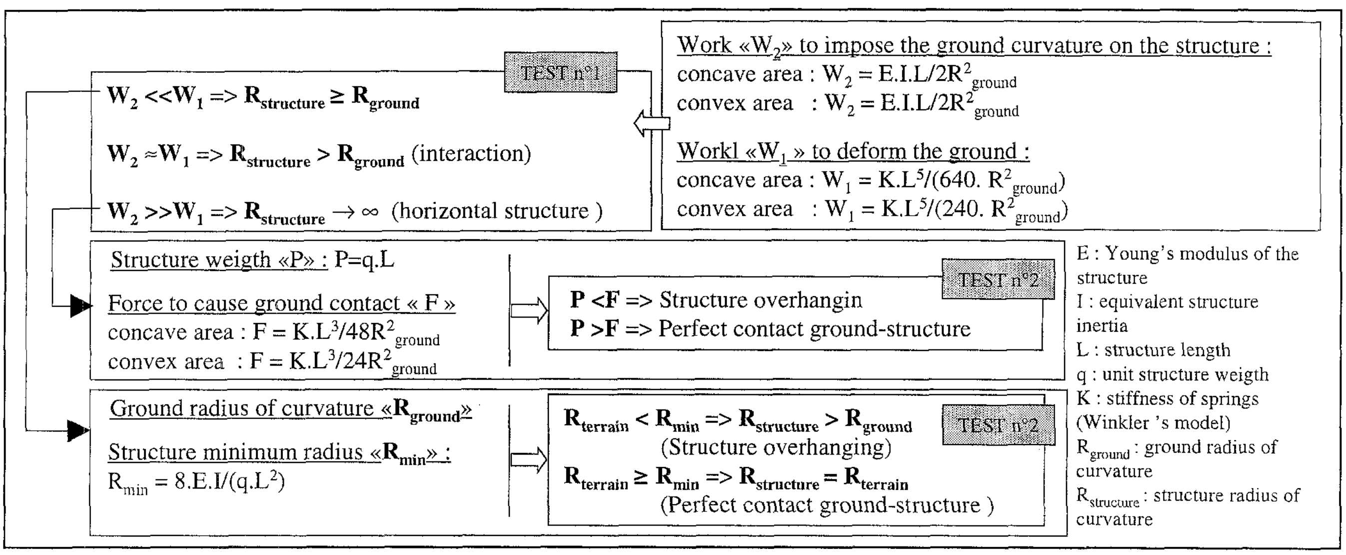


Figure 7 : Methodology for estimating whether the ground curvature is imparted to the structure.

A detailed development of the calculation is done for the case of a concave area. A similar approach can be adopted for the case of a convex area. The ground is modelled by spring elements (Figure 6). adopting the Winkler model. The latter assumes that the spring elements do not interact between each other. Each spring is thus characterised simply by its stiffness "K". A number of other more complex models (Henry [8]) have been developed, which could be adopted if necessary. The difficulty with such a model is to select a value for the stiffness "K". If it is assumed that there is a rigid substratum at a depth "h", it is possible to estimate the stiffness as a function of "h" and the ground mechanical properties (Figure 6). If there is no rigid substratum at depth, the height "H" that is required to define the springs stiffness can be estimated from knowledge of the initial settlement under a uniformly loaded foundation. Milovic [9] proposes, for example, an estimation of this settlement in different situations. The main stages in calculating the force and the work required to deform the ground are presented in Figure 6. If it is assumed that the structure length "L" is negligible compared to the ground curvature "R", the formulas for the force and the work of the deformation forces " W_1 " are greatly simplified. To calculate the structural deformation work "W_2", only the work of the bending moments is considered, the work of the shear force being neglected. By imposing a constant curvature along the structure, a constant moment is also imposed. For a unit length in the third dimension, the work "W_2" can then be calculated easily with equation 1.

$$W_2 = \frac{1}{2}\int M_f . \frac{M_f}{E.I} dx = \int \frac{E.I}{2R^2_{ground}} dx = \frac{E.I}{2R^2_{ground}} L \quad \text{(equ.1)}$$

Where "E" is the Young's modulus of the structure, "I" the structure inertia and "R_{ground}" the radius of curvature of the ground imposed on the structure. This equation assumes the classical hypothesis of trifling influence of shear work of the beam theory.

Figure 7 then summarises the method and the results. For a given ground radius of curvature and structure length, it is possible to compare the different works W_1 and W_2. The lowest indicates the most probable deformation mode, which corresponds to test No. 1 in Figure 7. According to the selected scenario, one then must determine whether the actual weight of the structure is sufficient to allow the structure or the ground to become deformed, which corresponds to test No. 2. The minimal radius that the structure can take according to its loading "Q" is calculated half-way along the structure length, assuming that the structure is simply supported at its two extremities (concave area) or at its centre (convex area). An identical radius of curvature of $8EI/qL^2$ is obtained.

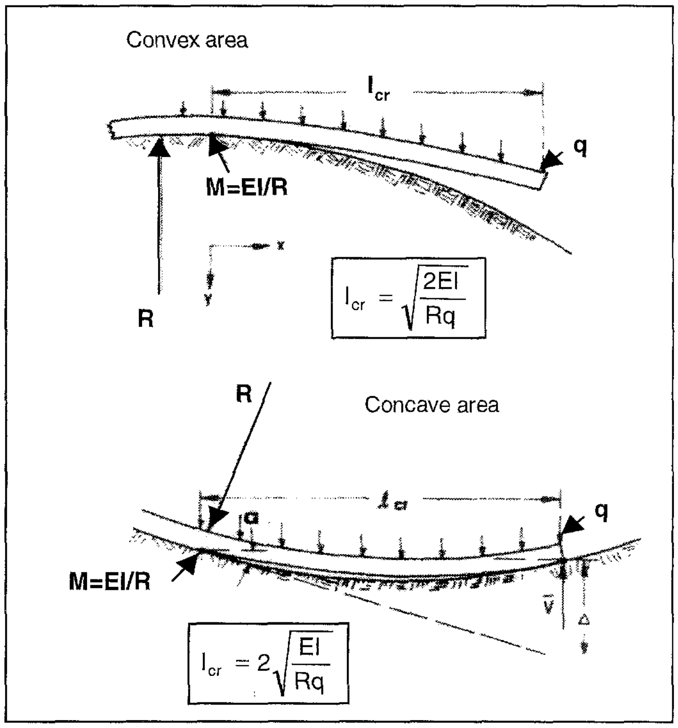


Figure 8 : Methodology for estimating whether the ground curvature is imparted to the structure (Yokel and al., [10]).

This methodology can be compared with that proposed by Yokel and al. [10] and shown in Figure 8. The latter sought to characterise the structure critical length at which the actual weight of the structure is sufficient for it to assume the ground curvature. This is equivalent to the above estimation of the radius of curvature, taking l_{cr}=L. A difference can be noted in the concave area. Indeed, Yokel and al. [10] consider that not only the structure is on two supports (corresponding to the moment M and the force V in Figure 8), but in addition the displacement of the extremity is imposed ($\Delta=l^2_{cr}/2R$). Neither of the approaches is completely realistic since it is impossible with a uniformly distributed loading to have a curvature which is constant, and thus equal to the ground curvature, along the structure. However, both approaches produce fairly realistic results.

3.2 *Estimation of the stiffnesses as regards ground horizontal strain*

Figure 9 schematically illustrates the approach for estimating of the stiffnesses as regards ground horizontal strain. The ground and the structure are modelled by two springs in parallel. As far as a horizontal movement is concerned, the behaviour of the ground will not be disrupted by the presence of a structure as long as the stiffness of the structure is low compared to that of the ground.

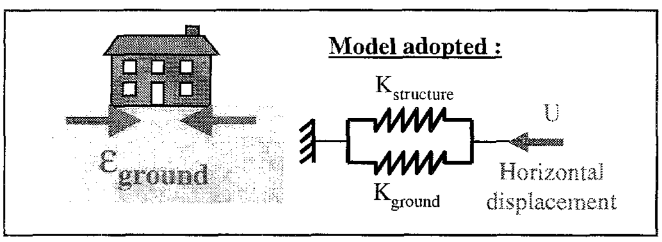


Figure 9 Approach to compare the stiffness of a structure against that of the ground with regard to horizontal strain of the ground.

The stiffness of the structure is modelled by different categories of frame structures as summarised in Figure 10. The parameters are as follows:

- Dimensions of the structure: height "h" and length "L", as well as the ratio "a" = h/L.
- Number of floors.
- Stiffness of the structural elements "EI" calculated by taking the product of the Young's modulus of the material "E" and the section inertia "I" of the considered element.
- The type of link with the ground and which depends on the type of foundation or the presence of basements. The links were considered to be articulated, embedded or with a stiffness to be determined in order to allow the model to be applied to various local structures.

The stiffness of the various structures are calculated analytically ; results are shown in Figure 10. An numerical investigation carried out to characterise the stiffness of a solid wall, has underlined the very strong stiffness of such a structure compared with the frame structure stiffness, with values ten to five hundred times higher.

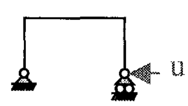
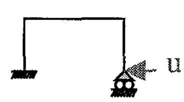
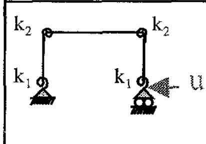
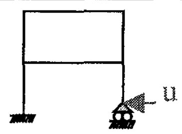
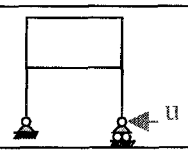
Caption	Model	Horizontal structure stiffness	Structure typology
E_1I_1 : posts stiffness E_2I_2 : beam stiffness k_1 : link stiffness between post and ground k_2 : link stiffness between post and beam h : floor heigth L : structure length a : « h/L » ratio K_s : structure stiffness		$K_s = \dfrac{1}{h^3(\dfrac{2}{3E_1I_1} + \dfrac{a}{E_2I_2})}$	One-level structure, with no basement, intermittent superficial foundations
		$K_s = \dfrac{6aE_2I_2 + 3E_1I_1}{2h^3 + \dfrac{ah^3E_2I_2}{E_1I_1}}$	One-level structure, deep foundations or superficial foundations with presence of a basement
		$EI = E_1I_1 = E_2I_2$ $K_s = \dfrac{EI\,[3 + 6a + \dfrac{6EI}{L}(\dfrac{1}{k_1} + \dfrac{1}{k_2})]}{h^3[2 + a + \dfrac{2EI}{L}(\dfrac{2}{k_1} + \dfrac{2}{k_2} + \dfrac{3}{k_1.a} + \dfrac{6EI}{k_1.k_2.h})]}$	One-level structure, stiffness of foundations and links to be adjusted
encassing link slide link hinged link hinged and sliding link		$EI = E_1I_1 = E_2I_2$ $K_s = \dfrac{3EI(a+1)(a+3)}{h^3(2a+3)(a+4)}$	Two-level structure, with no basement, intermittent superficial foundations
k link of stiffness k in rotation k slide link of stiffness k in rotation		$EI = E_1I_1 = E_2I_2$ $K_s = \dfrac{3EI(2a^2 + 9a + 8)}{h^3(a^2 + 6a + 7)}$	Two-level structure, deep foundations or superficial foundations with presence of a basement

Figure 10 : Horizontal stiffnesses calculated for the various types of structures modelled.

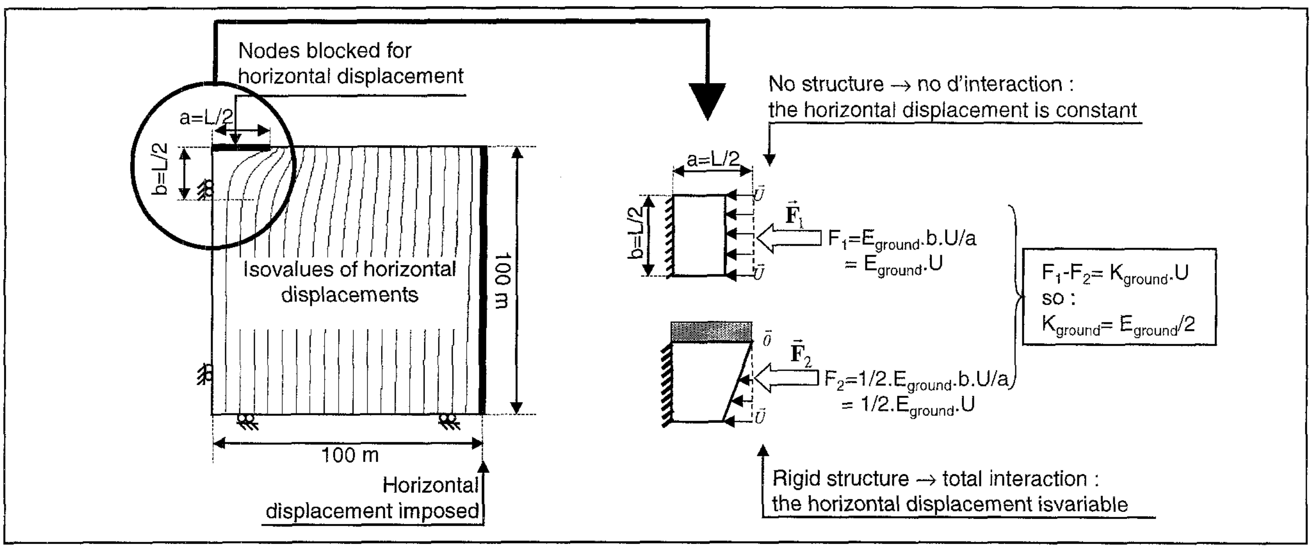


Figure 11 : Horizontal stiffness of the ground. Blow up shows a portion of the ground increasing its own stiffness.

Table 1: Description of the various numerical investigations carried out

Investigation of the effect of the various stresses for constant mechanical properties.		
Purpose	Mechanical properties taken into account	Movements investigated
Investigation in a ground curvature area	E_{ground}: 100 MPa $E_{structure}$: 5000 MPa	Concave and convex radius of curvature: +/-7500, +/-5000, +/-2500 et +/-1000 m
Effect in a ground horizontal strain area	E_{ground}: 100 MPa $E_{structure}$: 5000 MPa	Compressive and tensile strain: +/-10, +/-5, +/-2.5, +/-1 and +/-0.5 mm/m
Effect of mechanical properties for a constant stress		
Purpose	Mechanical properties taken into account	Stresses investigated
Investigation in a ground curvature area	E_{ground}: 30, 100 and 300 MPa $E_{structure}$: 1500, 5000, 10000 and 15000 MPa	Concave radius of curvature: -1000 m Convex radius of curvature: 1000 m
Effect in a ground horizontal strain area	E_{ground}: 30, 100 and 300 MPa $E_{structure}$: 1500, 5000, 10000 and 15000 MPa	Compressive strain. -5 mm/m Tensile strain: 5 mm/m
For all the investigations, the ground is considered to be elastoplastic: Young's modulus "$E_{terrain}$", Poisson's ratio 0,25, zero cohesion, angle of friction 30° and angle of dilation 10° For all the calculations, the structure is considered to be elastic: Young's modulus "$E_{structure}$", Poisson's ratio 0.2		

The ground stiffness is more complex to estimate analytically. It involves determining the ground area which takes part in its stiffness as regards the horizontal stress that is investigated. For this purpose, the surface area of the ground that is disturbed by the presence of the structure is examined. It is considered that the more a ground point is subjected to the specific weight of the structure, the more a change of state of this point is likely to generate a change of state of the structure. This methodology makes use of the "Maxwell-Betti" theorem used in structure analysis.

This estimation is carried out by a numerical investigation with the CESAR-LCPC V 3.2.4 finite element software[1] (Figure 11). A ground domain (100m*100m) loaded by a constant horizontal strain at depth is considered.

In addition, the horizontal displacement is blocked for a number of nodes at the upper border, over a length "L/2", in order to simulate a complete interaction between the ground and a structure of length " L ". The strain field is found to be disturbed by the presence of the structure (nodes blocked in displacement) over a depth approximately equal to half the length of the structure. As the calculation was carried out elastically, the ground

[1] Informations about CESAR-LCPC V. 3.2.4 are available on the web : http://www.lcpc.fr. This software is developped by the "Laboratoire Centrale des Ponts et Chaussées". Principales features are computation of underground works, civil engineering structures, seepage and heat tranfert.

stiffness was presumably overestimated. It can thus be assumed that the portion of the ground which takes part in stressing the structure is distributed, at most, over a depth approximately equal to the structure length. More specifically, the result of the numerical investigation highlights a fairly regular variation in the horizontal displacements under the structure. It appears that the contribution of the ground to its own stiffness increases with the proximity to the ground surface. This results in a ground stiffness which can be estimated to half its Young's modulus (Figure 11).

As the real phenomenon is three-dimensional, a unit extension must be considered to compare the two elements. The stiffnesses of the structural elements "EI" must thus be homogenised for a unit extension of the structure. If the stiffness of the structure is low as compared to that of the ground (figures 10 and 11), the structure is considered to be flexible and the horizontal movement of the ground is integrally transmitted to the structure. If, on the other hand, the stiffness of the structure is high as compared to that of the ground, the structure is considered to be rigid. The ground movement is then necessarily strongly disrupted by the presence of the structure, and this calls for a detailed investigation of the soil-structure interaction phenomena. For this purpose, the following section investigates the behaviour of a rigid structure of the load-bearing-wall type, with regard to mining subsidence.

4 Stress-strain investigation

This investigation is intended to highlight the overall behaviour of a solid-wall type structure, i.e. structure that is very rigid as compared to the ground. For this purpose, a set of numerical simulations was carried out in order to investigate the behaviour of a structure with regard to each basic loading components: horizontal strain and curvature. The effect of the slope was not investigated since the slope, as a rigid body movement of the structure, produces very little stress in the structure.

The finite element software CESAR-LCPC was used with six-node triangular elements, eight-node quadrangular elements and six-node interface elements. The latter elements make it possible to take into account a friction type behaviour as well as an interface separation. In all of the simulations, the ground behaviour was considered to be elastoplastic with a Mohr-Coulomb failure criteria ; the structure was considered elastic. The results shown below correspond to the structure and the soil-structure interaction before structure damage. This choice is justified considering the very high mechanical strength of the structure in comparison with that of the ground.

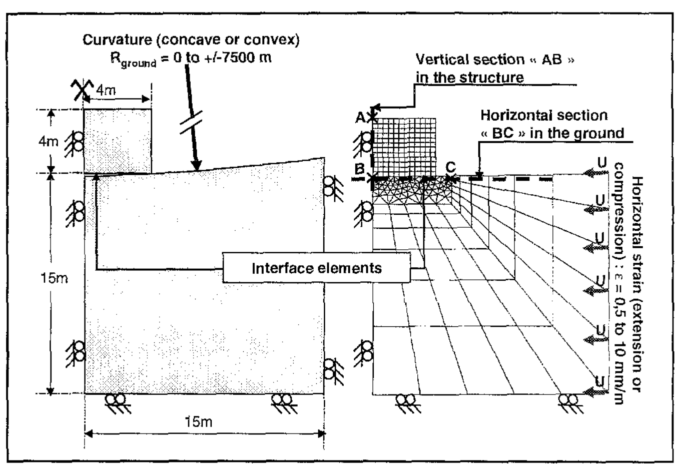


Figure 12 : Description of the models used to investigate the effect of the ground curvature and the horizontal strain.

Two sets of models were produced, and are shown in Figure 12. The first model is used to investigate the effect of a curvature of the ground. The second model considers the effect of a horizontal strain of the ground. The two models represent a ground domain measuring 15 m by 15 m, with a solid structure on its surface. The left border is a symmetry axis, and the calculations were carried out for plane strains. In order to simulate the effect of the ground curvature, the ground surface is modelled with a surface curvature (concave or convex curve) on which a perfectly horizontal structure is located. The interface elements between the structure and the ground are initially disconnected, except at the extremities of the structure for the concave area and at the centre for the convex area. The ground was consolidated under its own weight, then loaded by the weight of the structure. The results were analysed by considering stress components in the ground and in the structure, in particular along selected sections as shown in Figure 12. A particular attention was paid to the localisation of the failure points in the model.

In order to simulate the effect of the horizontal strain of the ground (tension or compression), an initially horizontal ground surface is consolidated under its own weight, then loaded by that of the structure and finally deformed by imposing a uniform horizontal displacement on the right border of the model. Different values of curvature and strain were investigated as well as different values of the mechanical properties of the ground and of the structure. The effect of each component of ground movement (curvature and strain) was first investigated for fixed values of mechanical properties ; then the influence a variation of these properties was analysed (Table 1). A description of all the investigations is first presented before results are discussed.

- Reference investigation: the consolidation of the ground under its own weight and the weight of the structure is investigated, with no additional loading.
- Investigation of the ground curvature: the effect of a concave and convex curvature of the ground with a radius of +/- 1000 m is investigated.
- Investigation of the horizontal strain of the ground: the effect of a tensile and compressive strain with an intensity of +/- 5 mm/m is investigated.
- Ground properties (elastoplastic): Young's modulus "E_{ground}" 100 MPa, Poisson's ratio 0.25, cohesion 0, friction angle 30° and dilation angle 10°.
- Structure properties (elastic): Young's modulus of the ground "$E_{structure}$" is 5000 MPa and its Poisson's ratio is 0.2.

4.1 Curvature analysis

The effect of the ground curvature on a structure is easy to understand as illustrated in Figure 3 that shows different diagrams of the operating mechanism in a curvature area. A concentration of vertical stresses at the ends of the structure is expected in a concave area and at the centre in the convex area in the centre. The schematic diagrams of Figure 3 can be compared to the results obtained with numerical modellings, Figure 13 and 14. These figures respectively show the results in the entire model and along two sections shown in figure 12 and located horizontally at a depth of 15 cm in the ground (section "BC") and vertically in the centre of the structure (section "AB"). Interesting aspects of these results are discussed below.

- Failure area differs from the failure area obtained in the reference investigation. The plastic points are concentrated perpendicularly to the areas on which the structure rests preferentially. These points are thus deduced from the high values of the vertical stress. Failure which occur at the right hand edge of the model is the consequence of the mesh size in these area and of the zero cohesion of the ground.
- The representation of the principal stresses highlights remarkably the stress redistribution in the ground. Stresses observed in the structure reflect a bending movement, consistent with the ground curvature. However, the structure curvature is never as high as the ground curvature. The structure stiffness is such that it retains a horizontal geometry.
- The analysis of the vertical stress under the structure shows that the disturbances are greater for a concave curvature than for a convex curvature. The vertical stress in the ground, underneath the area on which the structure rests preferentially, increase by 60% in convex areas and by about 100% in concave areas. In addition, a structure is more likely to be found partially disconnected from the ground in the concave area than in the convex area. This support the intuitive approach adopted by Kratzsch [5], who suggested that the structure remains horizontal as compared to that of Boscardin and Cording [6], who suggested that the curvature of the ground is transmitted to the structure. It appears that the separation is actually not related to the bending flexibility of the structure but instead to the vertical flexibility of the ground.
- The horizontal stress increases proportionally to the vertical stress. This increase is due to the lateral behaviour of the ground under a vertical load (Poisson's ratio), tempered by the failure criteria.
- The shear stress under the structure reveals a limitation of our modelling. Indeed, the solving process for elastoplastic computation lead to be in search of convergence the calculations. In spite of a satisfactory convergence in the concave area, a strange variation is observed of the shear stress under the structure. The only average value appears consistent in spite of other variations. This phenomenon is indicative of a numerical problem. Moreover, an observation of the iso-values of plastic strains has highlighted high plastic strain under the structure, up to 4.5%, very locally in a concave area and 1.4% in a convex area.
- The state of stress in the structure is consistent with all of the previous results. Tensile stress appears in the lower edge (0.1 MPa) in convex areas and in the upper edge in concave areas (0.24 MPa).

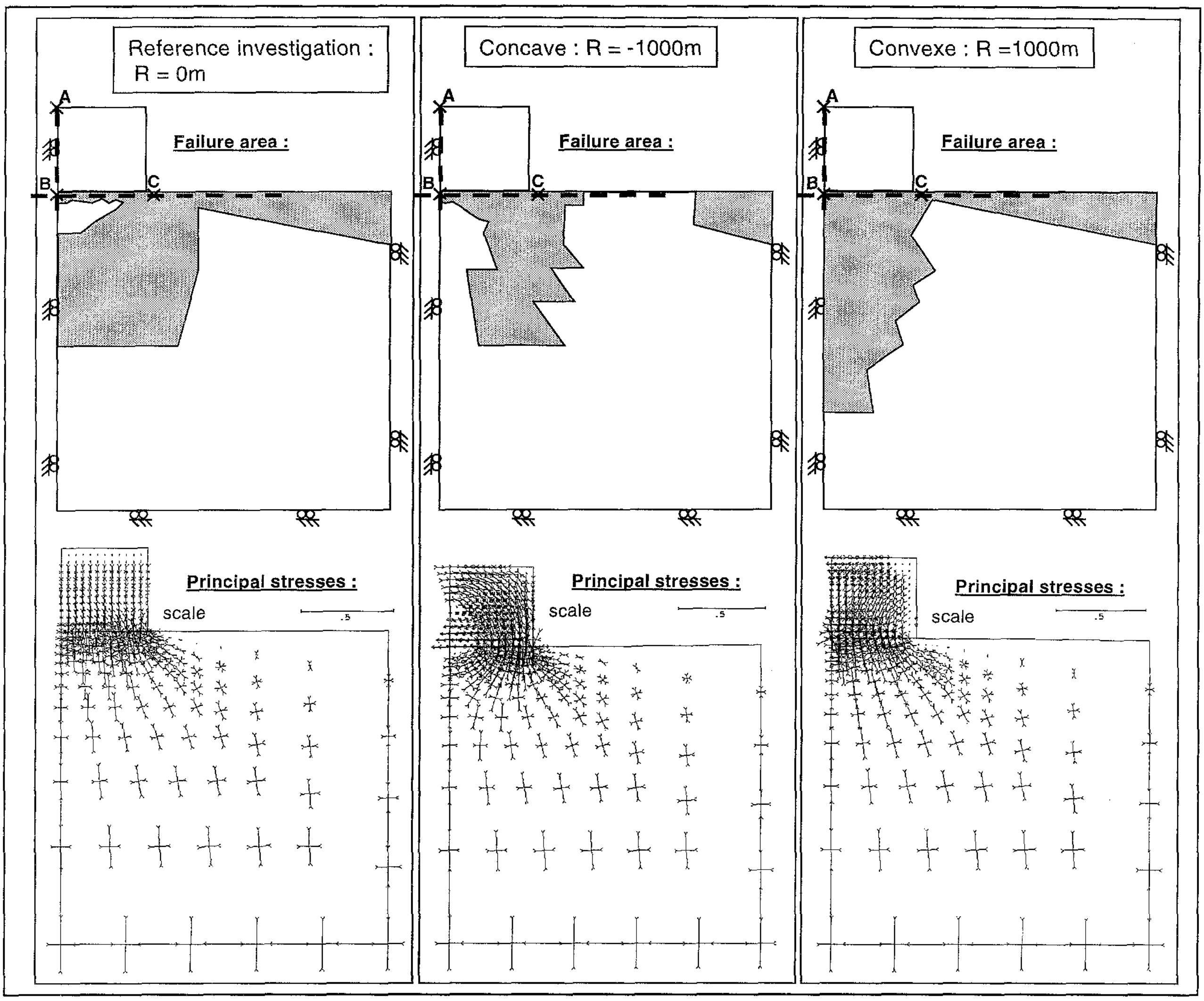


Figure 13 : Stress fields and failure areas in a curvature area (+/- 1000m)

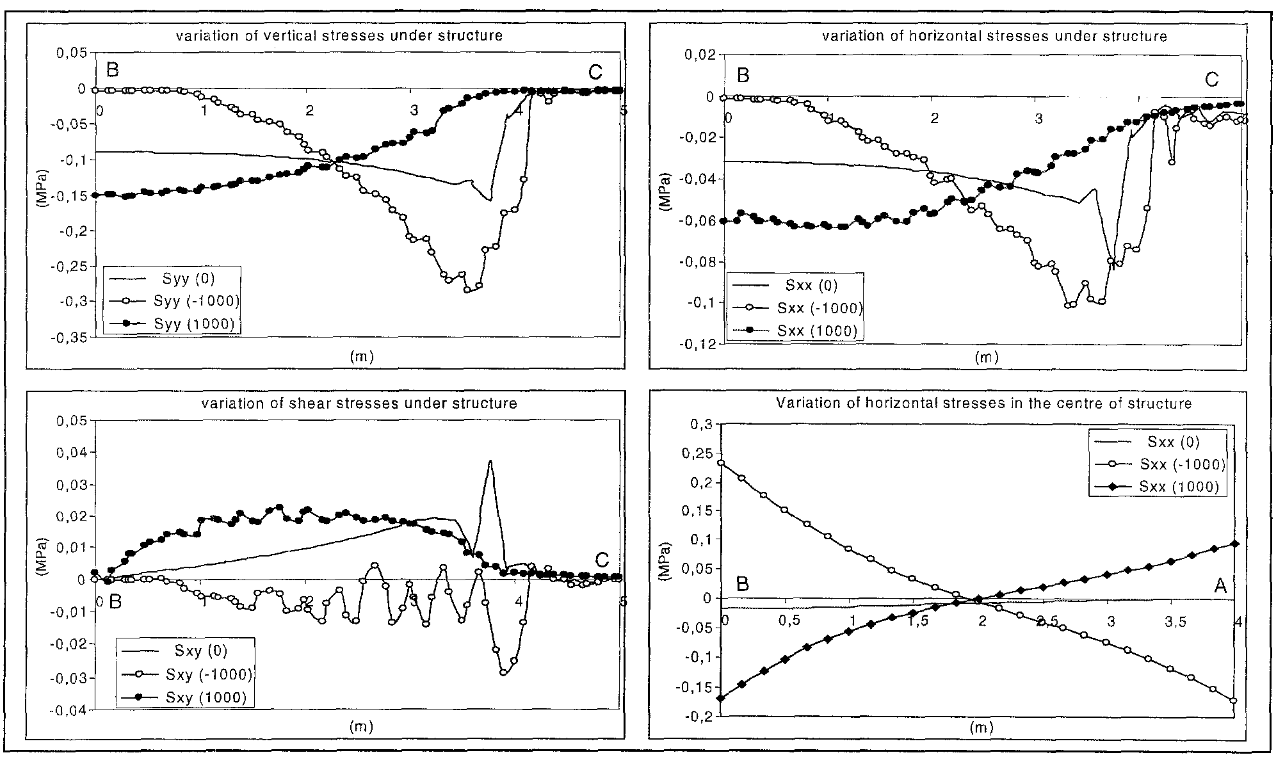


Figure 14 : Stresses along a horizontal section under the structure and along a vertical section in the centre of the structure in a curvature area (+/- 1000m)

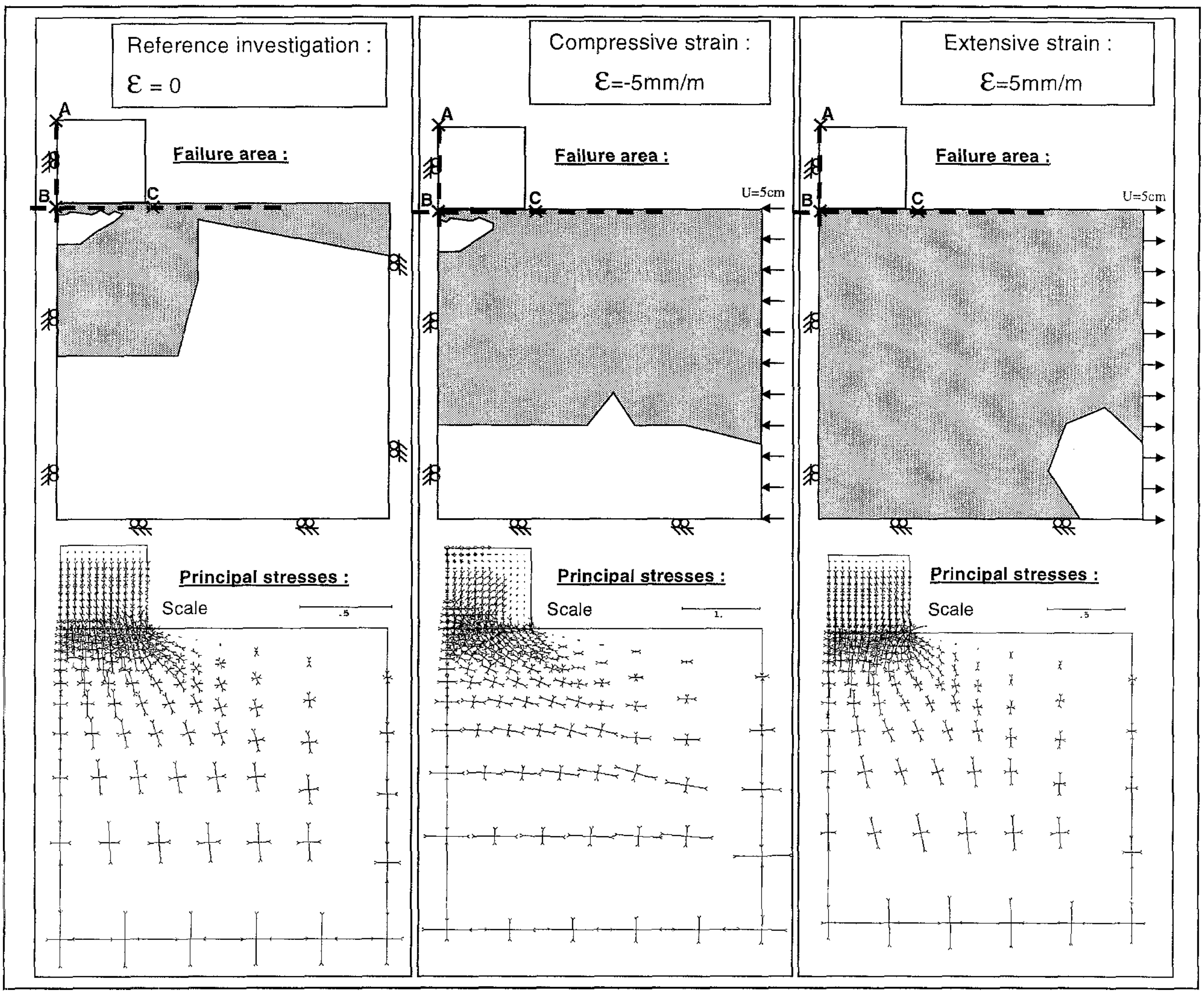


Figure 15 : Stress fields and failure areas in a strain area (+/- 5mm/m)

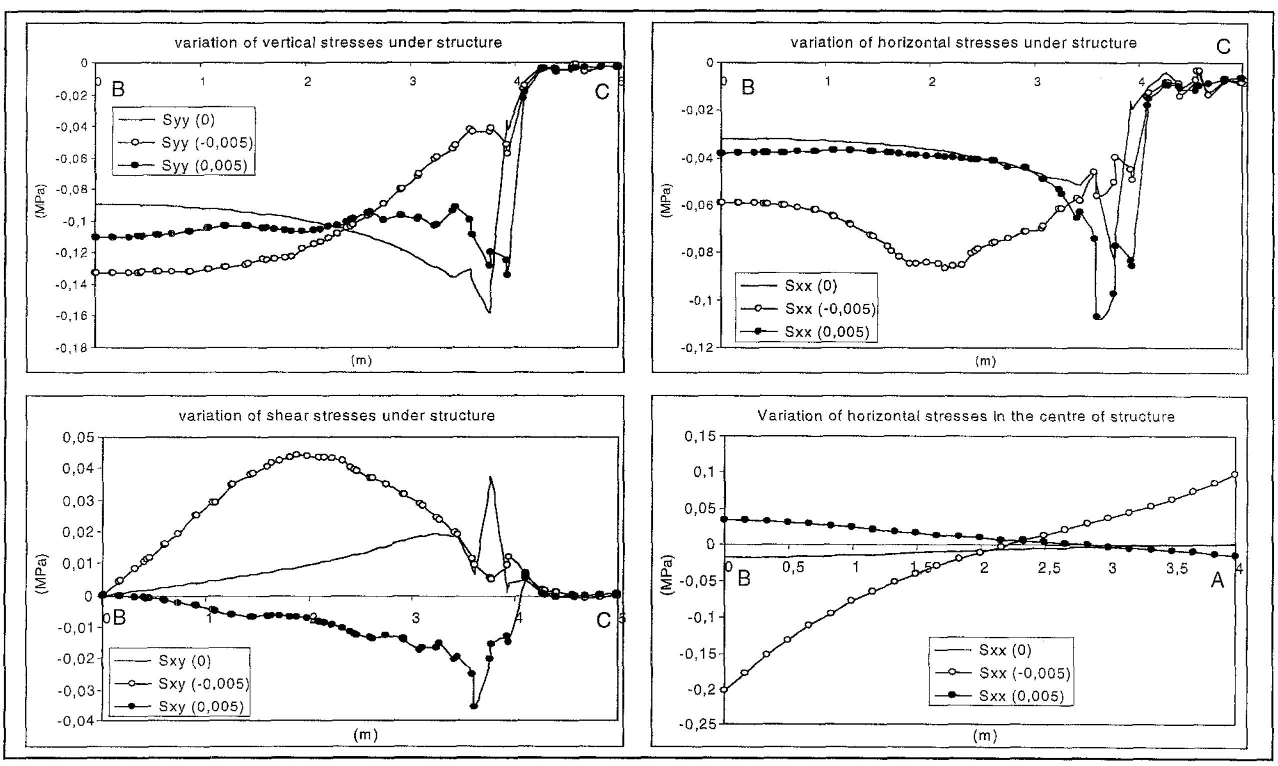


Figure 16 : Stresses along a horizontal section under the structure and along a vertical section in the centre of the structure in a strain area (+/-5mm)

4.2 *Strain analysis*

In the same way as for curvature, the effect of a horizontal strain of the ground on a structure has often been grasped qualitatively (Figure 4). The main idea adopted so far has been to assume that the horizontal strain of the ground only produces a uniform horizontal strain in the structure. The investigation presented here provides a visualisation and a quantitative analysis of the behaviour of a structure under such a load. The results are shown in Figure 15 and 16.

- The failure points in the model vary differently according to the strain direction. A generalised failure in the model can be observed in the tensile area, which can be readily understood given that the strain tends to decrease the horizontal minor stress whereas the vertical major stress remains unchanged. In compression areas, however, a confined area is observed under the structure, similarly to that obtained with the reference investigation (structure resting on a flat soil without strain) and which is similar to the cone of ground which shape is preserved under a vertically loaded foundation.
- The stress field in the model shows that a compressive strain generates a stress concentration in the ground under the centre of the structure as well as bending stresses in the structure. In a tensile area, however, the stress field seems to be relatively little modified in the ground and in the structure.
- The variation in vertical stress under the structure provides a good representation of the overall behaviour. The compressive strain leads the structure to rest preferentially on its middle section. The stress increase is then about 40%, i.e. an value comparable to that observed for the curvature. In tensile areas, however, a re-homogenisation of the vertical stress is observed under the structure.
- The horizontal stress in the ground increases only slightly in tensile areas. In compressive areas, however, a penetration of the horizontal stress under the structure can be observed and no increase in these stresses is observed towards the outside of the structure. Indeed, the presence of the free surface does not allow a significant increase in the horizontal stress as the vertical stress is very low. It is of interest to compare this result against one of the remedial actions that is proposed to minimise the effect of the strain: the digging of trenches around the periphery of the structure is often mentioned as a technical solution. The stress on the ground surface proves to be low on account of the adopted failure criterion (Mohr-Coulomb). Therefore, such a solution does not completely cancel the effect of the strain.

  A shearing phenomenon appears naturally under the structure. Contrary to what is often assumed (Kratzsch, [5], the value of the shear stress is not constant. In a compressive area, the variation in the shear stresses is more complex than in a tensile area. This phenomenon is associated with the distribution of the vertical stress which varies significantly along the structure.
- The structure is much less affected by the strain imposed by the ground than if such strain is imparted integrally. Indeed, a strain of +/- 0.005 mm/m has the effect of a horizontal stress of 25 MPa in the structure. Instead of such a value, the compressive area causes a compressive stress of –0.2 MPa in the lower edge and a tensile stress of 0.1 MPa in the upper edge ; the structure is

thus bent. To a lesser extent, the same phenomenon is observed in a tensile area since the latter tensile horizontal stain generates tensile stresses of 0.04 MPa in the lower edge and –0.02 MPa in the upper edge. The compressive stress distributed in the ground and the direction of the shear stress are both responsible for the bending that is observed.

4.3 Sensitivity analysis

A sensitivity analysis was carried out to evaluate the effect of the mechanical properties of the ground and of the structure on the results discussed above. Whole of the investigation are presented in Table 1 and the main observations are discussed below:

- All of the calculations showed that the mechanical properties of the structure have no effect on the results. In reality the structure is much more rigid than the ground in all of the calculations: The Young's modulus of the structure is at least five times greater than that of the ground, and the calculation for plane strains leads to an overestimation of the structure stiffness.
- An increase of the ground Young's modulus leads to an increase of the phenomena described above. In a curved area, it can be seen that the disconnected length of the structure increases with a higher modulus of elasticity of the ground (100 MPa) and disappears completely with a lower modulus (30 MPa).
- The horizontal stress in the structure increases and show a bending moment which increases as the ground stiffness increases.
- Irrespective of the selected mechanical properties, the stress state in the ground and in the structure is more disrupted in a concave area than in a convex area.
- An increase of the plastic strain value is observed in the model with increasing of the ground modulus of elasticity. In particular, the analysis of a compressive strain with a ground Young's modulus of 300 MPa gives clearly inconsistent results. The model thus produced does not make it possible to describe the behaviour of a ground domain subject to large plastic strain.

An overall picture of the numerous quantitative results that was obtained is provided by series of value of tensile stress in the structure observed in the different models. Figure 17 and 18 provide a rapid comparison of each investigation. It can thus be seen in Figure 17 that for a ground modulus of elasticity of 100 MPa, a radius of curvature of +5000 or –7500 m generates the same tensile stresses as a strain of –0.5 or +2.5 mm/m. Figure 18 allows this same comparison to be made when the ground's Young's modulus varies. As an example, a radius of curvature of 1000m of a ground characterised by a Young's modulus of 30 MPa, generates the same stress in the structure as a extension strain of 5 mm/m in a ground with a modulus of 100 MPa.

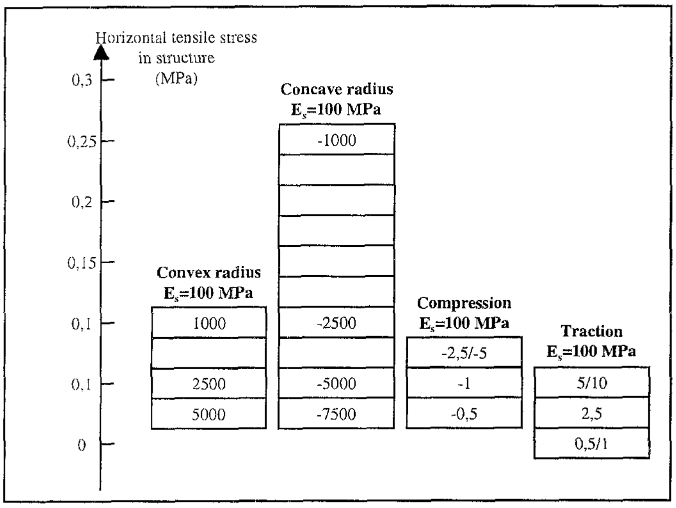


Figure 17 : Tensile stress observed in the structure for different loadings and for a constant ground Young's modulus of 100 MPa.

The ground movements that apply a larger load to the structure are, in order of importance: a concave curvature, a convex curvature, a compressive strain and a tensile strain.

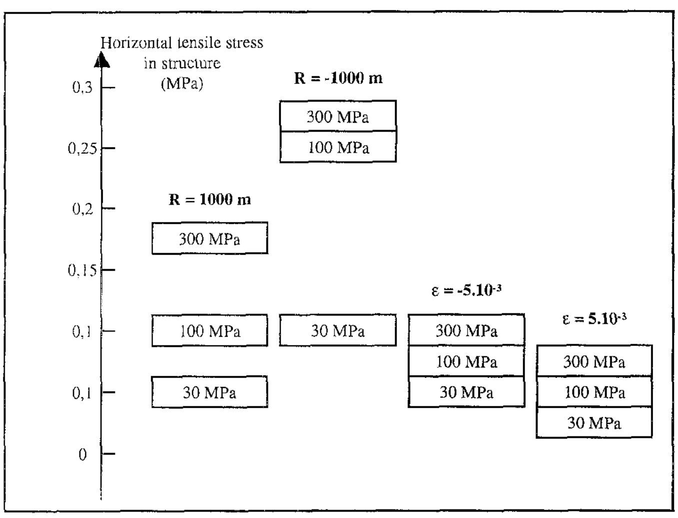


Figure 18 : Tensile stress observed in the structure for different loadings and for different values of the ground Young's modulus.

It can also be seen that the ground mechanical properties have a relative greater influence on the effect of a curvature than on the effect of horizontal strain.

Using the set of results shown above, diagrams can be constructed of the behaviour of a structure in a curvature area or in a strain area. These models are shown in Figure 19 and 21. These figures show the location of slippage lines and the distribution of the vertical stress in the ground and under the structure at various depths. A comparison with Figure 3, 4 and 20 reveals that some aspects are similar, in particular, the slip lines proposed by Speck and Bruhn [7] or Kratzsch [5] are fairly similar to that shown in Figure 21. This confirms our results, since the slippage lines have been observed experimentally on scale models in sand. The horizontal stress observed along the middle section of the structure is also highlighted. The stress is shown as a function of a parameter "a" for the single purpose of being able to make comparisons between them. This state of stress corresponds to the investigation presented in detail in Figure 13 to 16 (E_{ground}=100 MPa, $E_{structure}$=5000 MPa). It is possible to adjust this state of stress, for other cases, using the synthetic results of Figure 17 and 18. This distribution of stress may be compared to the distribution proposed by Kratzsch [5] and shown in Figure 20. The difference is, however, that his approach superimposes the effects of curvature and horizontal strain. In view of the adopted failure criteria and of the extent of the plasticity that is observed, superimposing the effects of basic stresses is not possible for deducing the actual loading. A global model must then be used to load a structure simultaneously by a curvature and a strain (Deck and al., [11]).

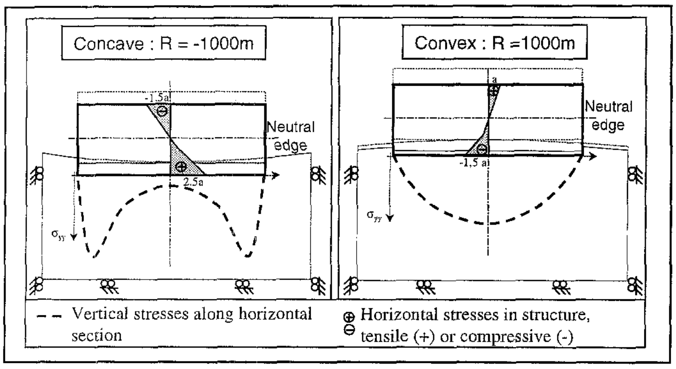


Figure 19 : Behaviour of a structure with regard to a ground curvature.

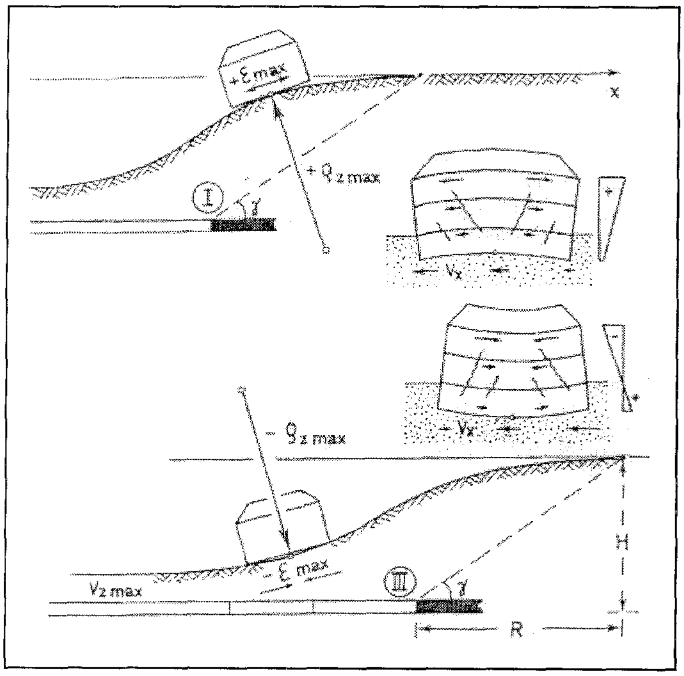


Figure 20 : Horizontal stress in a structure subjected to a curvature and a strain (Kratzsch, [5]).

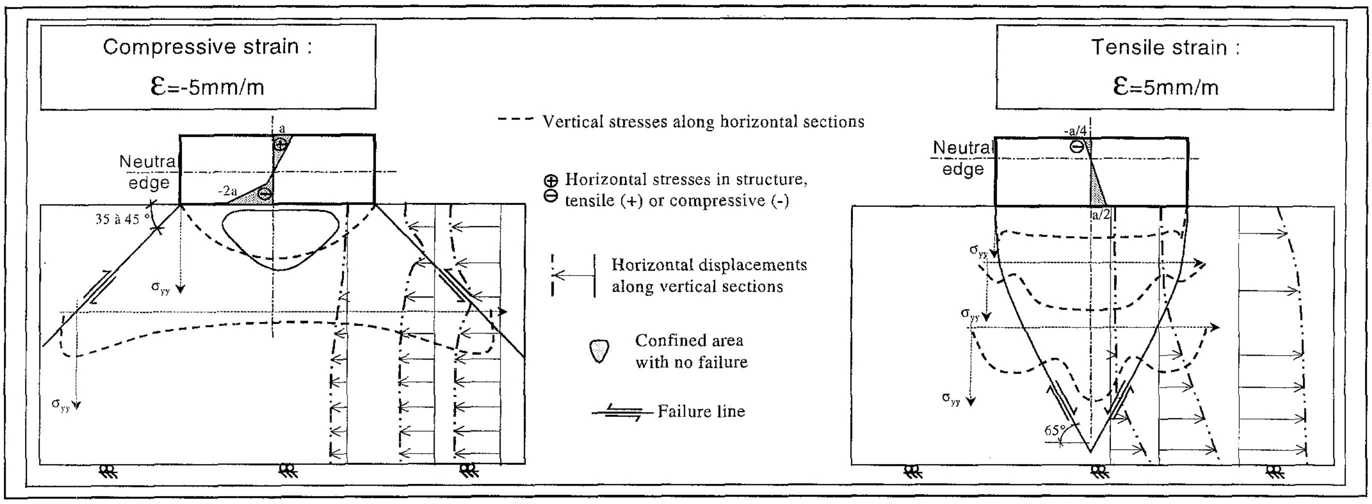


Figure 21 : Behaviour of a structure with regard to a ground horizontal strain.

5 Conclusions

This study describes soil-structure interaction phenomena at work during a mining subsidence. The structures are loaded in particular by ground curvature and strain. The cases where ground movements are integrally imparted to the structure are distinguished from those showing a strong interaction. The problem is simplified by dissociating the ground curvature and the strain. Our analysis provides a better determination of the different behaviours of the ground and of the structure under the effects of these different components of the ground movement. However, the combination of these structure loading sources still remains to be investigated. The main results of our investigation are summarised as follows:

- The investigation of the mechanical work needed to deform the ground of the structure in a curved area made it possible to distinguish the cases in which the curvature is certainly imparted to the structure, from the cases in which it is not. By considering the structure specific weight, it is also possible to estimate whether the structure is partially disconnected or whether it rests fully on the ground.
- Modelling a structure by beam elements assembled together by hinged joints of variable rigidity makes it possible to evaluate a structure ability to be deformed horizontally. It is possible to compare the resulting structure stiffness which results from the ground stiffness. This method makes it possible to distinguish cases in which the ground horizontal strain is imparted to the structure, from other cases.
- The behaviour of a flexible structure with regard to the ground may be investigated by means of structure calculation software, imposing the ground displacements to the structure. The phenomena at work when the structure is rigid and such transmission is not complete, was investigated by considering the behaviour of a rigid structure in a curved area and in a strained area.
- Numerical modelling has provided comparison between the effects of the different loadings and the effects of the ground mechanical properties.

- The investigation of the ground curvature is consistent with the behaviour from intuitive models devised to date.
- The strain investigation shows that this aspect is more complex than assumed until now. In particular, strain causes a bending moment in the structure that is not negligible compared with the one induced in the curvature area. Tensile strain also produces immediate rupture in the ground which prevents the stress from being imparted to the structure.
- We propose overall behaviour models of a structure in a curvature area and in a strain area. The latter provides a better understanding of the phenomenon and a better assessment of the effectiveness of the preventive measures that are proposed to protect buildings.
- The overall behaviour model that we propose in a tensile area suggests that the structure stability cannot be guaranteed unless the ground is secured. However, such instability cannot be described by the numerical model that was used.

6 Bibliography

[1] WAGNER and SCHÜMANN (1991). Surface effects of total coal-seam extraction by underground mining methods. J.S. Afr. Inst. Min. Metall., Vol. 91, No. 7, Juillet 1991, pp.221-231.

[2] WHITTAKER B. N. and REDDISH D. J. (1989). Subsidences : Occurrence, Prediction, Control. Elsevier.

[3] MERWE (Van der) J. N. (1986). Analysis of surface subsidence over a longwall panel at 50m below surface. In SANGORM symposium : The effect of underground mining on surface, Octobre 1986.

[4] RAUSCH, extract from Mining Subsidence Engineering (Kratzsch [5]), Springer-Verlag.

[5] KRATZSCH H.(1983). Mining Subsidence Engineering, Springer-Verlag.

[6] BOSCARDIN M.D. and CORDING E.J. (1987). Building response to excavation-induced settlement. Journal of Geotechnical Engineering, Vol. 115, No. 1.

[7] SPECK R.C. and BRUHN R.W. (1995). Non-uniform subsidence ground movement and resulting surface-structure damage. Environmental and Engineering Geoscience, Vol. 1, No. 1, pp. 61-74.

[8] HENRY F.D.C. (1986). The design and construction of engineering foundations. Chapman and Hall Ltd, edited by Henry F.D.C..

[9] MILOVIC D. (1992). Stresses and displacements for shallow foundations. Elsevier.

[10] YOKEL F.Y., SALOMONE L.A. and GRAY R.E. (1982). Housing construction in areas of mine subsidence. Journal of Geotechnical Engineering, Vol 108, No. GT9.

[11] DECK O., AL HEIB M. and HOMAND F. (2001). Study of consequences of mining subsidence on buildings by numerical modelling (Etude des conséquences des affaissements miniers par la modélisation numérique). 15e French mechanical engineering congress, Nancy (September 2001).